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LONG-RANGE TUNA SCHOOL DETECTION SONAR SYSTEM DESIGN SPECIFICATION

Prepared by

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U.S. DEPARTMENT OF COMMERCE
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Southwest Fisheries Science Center

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Explanatory Note

This report is one in a series on the potential for technology applications to enhance efficiency in commercial fisheries, reduce the catch of non-targeted species, and provide new tools for fishery assessments in support of the NMFS strategic goals to build sustainable fisheries and recover protected species. A report synthesizing the results of this series of studies is planned. We hope the distribution of this report will facilitate further discussion and research into the application's potential usefulness, but should not be construed as an endorsement of the application by NMFS.

Pursuant to changes in the Marine Mammal Protection Act in 1988, the NMFS' SWFSC began another series of ETP-related studies in 1990, focused on developing and evaluating methods of capturing yellowfin tuna which do not involve dolphins. This series of studies has been conducted within the SWFSC's Dolphin-Safe Research Program. Studies on the potential use of airborne lidar (LIght Detection And Ranging) systems began in 1991, and studies on low-frequency acoustic systems to detect fish schools at ranges much greater than currently possible were initiated during 1995. In addition to their use as an alternative to fishing on dolphins, these systems have potential to increase the efficiency of the fishing operations by locating fish schools not detectable by customary visual means, and as a fishery-independent tool to conduct population assessments on pelagic fish. They also have potential to adversely impact marine animals.

The Dolphin-Safe Research Program is investigating, through a series of contracts and grants, five airborne lidars: 1) the NMFS-developed "Osprey" lidar (Oliver et al. 1994), 2) the Kaman Aerospace Corporation's FISHEYE imaging lidar (Oliver and Edwards 1996), 3) the NOAA Environmental Technology Laboratory's Experimental Oceanographic Fisheries Lidar (Churnside et al. 1998), 4) the Arete Associates 3D Streak-Tube Imaging Lidar, and 5) the Detection Limited's lidar . An initial study on the potential effects of airborne lidars on marine mammals will be completed during 1998 (Zorn et al. 1998).

The Dolphin-Safe Research Program has completed, through a series of contracts and grants, acoustic system studies on 1) the acoustic target strength of large yellowfin tuna schools (Nero 1996), 2) acoustic detection parameters and potential in the eastern tropical Pacific Ocean (Rees 1996), 3) **the design of** two **towed acoustic systems** (Rees 1998, **Denny et al. 1998**) and, 4) the potential effects of low-frequency sound on marine mammals (Ketten 1998). Studies are in progress to measure swimbladder volumes from large yellowfin tuna and to determine experimentally the effects of blast and acoustic trauma on marine mammals. During 1998, the SWFSC plans to measure the acoustic sound field produced by tuna seiners (and possibly a research vessel) and to obtain direct measurements of the acoustic target strength of tuna schools.

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Dolphin-Safe Research Program Detection Technology Reports

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NOAA Technical Memorandum

Long-Range Tuna School Detection Sonar System Design Specification

A report of the Scientific Fisheries Systems, Inc.

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Executive Summary

This document describes a design for a prototype long range tuna detection sonar system to operate in the Eastern Tropical Pacific (ETP). The following points are a brief summary of the system's significant attributes:

- Self-contained portable towed system, with electro-hydraulic winches, projector and hydrophone array, and control and display system.
- Size: Projector: ~18" x 18" x 24" on 155' (50m) electro-mechanical cable
  Receive Array: ~4" diameter x 40' (13m) long on 1250' (400m) electro-mechanical cable.
- Power: 2000 KVA (input), (196 dB//1µPa source level) from on deck power supply (220VAC input).
- Receive array power: electrically quiet Ni-Cd batteries, rechargable throught the cable.
- Maximum nominal range: 18 NMi. (30 Km) in deep water on schools of at least 10 Tons size schools. This range could vary from 8 Km to 50 Km with different conditions.
- Horizontal coverage: 180° in 17 beams.
- Frequency: 4 KHz CW pulse, and 3-4 KHz Broadband pulse.
- Low Cost: Commercial-Off-The-Shelf (COTS) components can be obtained for ~$100K.
- Low Risk: Based on use of COTS components and techniques developed for the Navy over the past 30 years.

The system has some limitations which require special operating considerations:

- Maximum speed while operating is 8 knots, therefore sprint and drift search techniques are necessary.
- Maximum towing speed with the arrays deployed: 15 knots.
- Maximum depth of the receive array: 310' (100m)
- Maximum depth of the projector: 55' (20m).
- Maximum range will decrease with increasing speed or increasing Sea State.

Background

This design is based primarily on 3 inputs:

1. Model Estimates of Acoustic Scattering from Schools of Large Yellowfin Tuna (1996) by "Woody" Nero (NRL/SSC),
2. Modeling of Acoustic Detection of Yellowfin Tuna in the Eastern Tropical Pacific Fishery Area (1996) by David Rees (NCCOSC/RDT&E c/541) and
3. Conversations with the Advisory Committee with emphasis on inputs from Capt. Harold Medina.

The following subsection discussions address several major topics that provide a basis for the design. The remainder of the document is devoted to the sections dedicated to the major components of the system.

Frequency Selection

The first consideration for this system is the operating frequency range. Rees' work relies on the Target Strength (TS) projections developed by Nero, and is primarily a study in propagation transmission loss (TL) and Probability of Detection (P_D) with a matrix of assumptions regarding school size, composition, orientation and depth for 4 "typical" areas in 4 seasons. Rees' work examined the frequency range from 100 Hz to 20 KHz and recommended a 5 KHz pulsed system with a towed array receiver and a maximum commercial source strength as the most viable commercial system. Nero suggested 2 broadband frequency regimes: 50 Hz to 2 KHz and 2-5 KHz based on TS projections. Note the TS models are supported by experimental data[1,2,3] over a wide range of oceanic conditions and fish species. A long range system has been built in Britain using 1 and 2 KHz transmitters achieving 65 Km detections, but having a shore based transmitter with source levels of 235 and 224 dB//µPa @ 1 m, at each respective single frequency[4].

Nero based his frequency recommendations on the swim-bladder resonance phenomena. Tuna are projected to have a low frequency resonance, depending on animal size and depth, from 83 to 630 Hz. A typical frequency response is shown in the accompanying Figure 1. At this resonance, TS values are +15 dB higher than the asymptotic high frequency case, which would provide a spectral feature for identification purposes. However, the problem is ill-specified, as one measurement alone is insufficient to determine animal size and depth. Also, any ostariost (bony fish with bones connecting the swim bladder to the ear) of similar size would render an indistinguishable response[5]. From a systems point of view with regard to physical capabilities, it also suffers from an extreme bandwidth (3+ octaves, or Q « 1) where projectors are large and expensive. The higher band, utilizing the full bandwidth, was also recommended because schools of smaller fish will have resonances in this area[6] and therefore can be identified as non-tuna, or at least undersized tuna and avoided. Nero obtained his broadband data with SUS (explosive) sources, not an option for us.

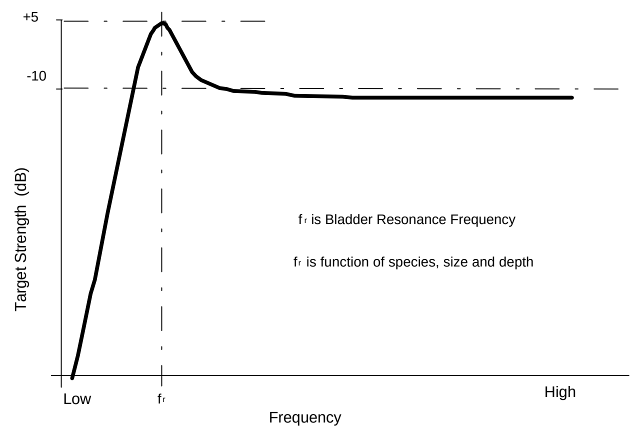

Figure 1 Typical Swim Bladder Resonance Shape

Rees' work also indicates that the 1-5 KHz band often has enhanced propagation due to the existence of surface ducts (similar to wave-guide channels in microwaves) in his groups 0 and 3 Sound Velocity Profiles (SVPs). When these conditions exist, and the fish are in the duct, very long detection ranges are possible, and this should be exploited in the operational system. In the remainder of the cases, spotty detection is possible at weak convergences over wide depth ranges. For design purposes the standard propagation, $TL = 20 \log_{10} (R) + \alpha R$ (where R is range in meters and α is the frequency dependent acoustic absorption coefficient) is a reasonable design criteria with actual (or modeled) TLs being higher or lower than that estimate. This is also a frequency region where naval sonars have operated for up to 40 years, thus the technology is well known and risk is reduced. Some care should be taken in using this band as there is 1 report of decreased catches of albacore, a related species, due to the ship's radiated signature with content over 1500 Hz[7]. However, another report questions this result because of the reduced hearing sensitivity in tuna above 1000 Hz[8].

This frequency band is well above the region for fin-beats and below that of dolphin calls. To include these frequency ranges for identification cues of targets would be prohibitive in terms of processing capability and loss of detection range by inclusion of the added noise in particularly the lower range.

Vertical Directivity.

An element of oceanic noise can and should be exploited here: the vertical noise structure. Each of the elements in the array are omni-directional in nature over at least the band of interest. The beam formation produces a cylinder of sensitivity, "looking" in cross-section like a bow-tie, that integrates sound from the surface, bottom and both sides into 1 level. Figure 2 shows 2 characteristic phenomena that are observed because of the nature of the noise sources: a low frequency, nearly horizontal propagation, and a high frequency vertical propagation. Low frequencies propagate via convergence-zone methods and arrive ±12 degrees from horizontal, while high frequencies are usually locally generated by wind, wave action and moisture falling onto the surface, as well as biologically generated bubbles. This gives high levels from the surface, approximately 10 dB lower from the reflected bottom signal, and an almost void in the horizontal. Low frequency, in this case, is below 1 KHz, while high frequency is considered from about 3-4 KHz and up. Thus there is array gain to be exploited by removing this vertical component of noise from the array. Two mechanisms to accomplish this are available: a hard acoustic boundary, or by absorption. The boundary method invokes the use of compliant structures which are essentially air filled and provide a new boundary to the array. The absorption method relies on material characteristics to deaden the sound. The null in the horizontal of the high frequency case is at least 50 dB. By concentrating the sensitivity of the array elements to only that zone, which is where we would be transmitting, we could theoretically get a 50 dB gain, from this technique alone, against omni-directional receivers. This gain is in addition to the horizontal gain achieved by the line array beamforming. One point of concern is the unknown behavior of the notch at SS0 conditions, when the sole contributor will be biologically generated bubbles.

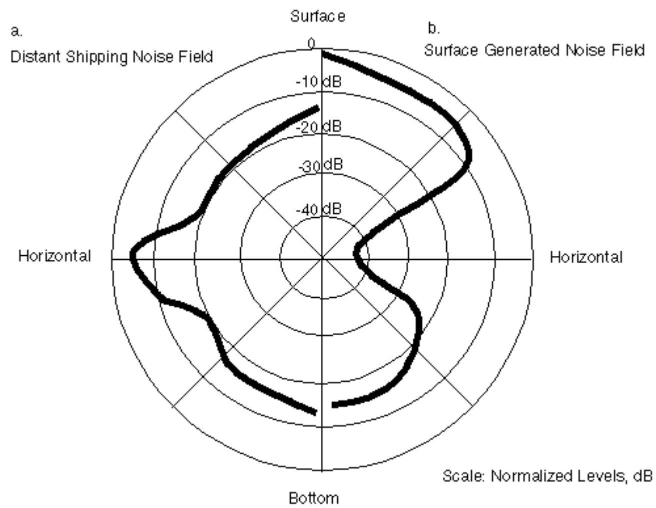

Figure 2 Sample Vertical Noise Distributions

Practical solutions to achieving this discrimination are not without fault, however. The compliant boundary method suffers from having a rigid structural member in the array, which usually increases drag and flow noise. It is also the most risky and costly approach. The absorbent boundary is material dependent, which is frequency dependent and often dependent on depth of operation. Absorbent materials can be counted on, typically, for at least 10 dB of help. The first 10 dB of gain required 11-13 elements and ~$6000 per octave. Getting another 10 dB for $50 at low risk is too much of a bargain to avoid.

Target Strength.

An estimate of the physical size of a commercially viable school of tuna will allow estimation of the acoustic target size which the sonar will have to detect At the lower end, a school amounting to 16 tons of caught fish is considered a small commercial amount. If we assume, although conservatively, that the whole school is actually brought aboard in the nets, the 16.5 ton is a nominal size and we can use a 10 ton size as a reasonable lower limit for detection. At the other end, a haul of 100 tons is considered a good catch. It is reasonable to assume that the tuna school from which 100 tons has been caught is actually somewhat larger for the purpose of detection, however, the calculation of the target size for sonar purposes will be accomplishes using the 100 ton value.

Nero’s work bounds the body length range of the tuna to an average of one meter. Reference to various fishing articles and sport fisherman’s guides puts the weight of a fish of this size at about 15.5 Kg. Using this figure, the 10 ton school has approximately 643 animals. The 100 ton school has about 6,430 animals. For convenience, numbers have been rounded

Nero estimates that the target size of tuna in the frequency region above 3 KHz is - 30 dB normalized to one fish. For the 3 lengths of his estimate, this translates to TS values for the school of +0.9, +1.6 and 2.5 dB. Using our limiting case, scaling the school target size by RMS addition of the individual target size of n fish provides the following results:

$TS_{10\ Ton} = -30\ dB + 10 \log_{10}(640\ fish)$
$TS_{10\ Ton} = -2.0\ dB_{TS}$

$TS_{16\ Ton} = -30\ dB + 10 \log_{10}(960\ fish)$ (Nominal or Criterian school size)

$TS_{16\ Ton} = 0\ dB_{TS}$

$TS_{100\ Ton} = -30\ dB + 10 \log_{10} (6{,}400\ fish)$
$TS_{100\ Ton} = +8.0\ dB_{TS}$

Via inputs from the Advisory Committee, the operational scenarios which would drive the choices of sonar system configuration became evident and are as follows:

- The tuna boat crew can now reliably spot the fish, and classify the school as tuna, at a range of 5 to 7 miles, dependent on “logs”, other animal sightings, or surface disturbances via on board or helo observations.
- Once within the range of visual detection, the boat crew has no further need for a sonar, and a deployed unit would be a hindrance to fishing operations.
- The boats now travel at 15 knots, and searches the volume in front and to the sides of its path. It is possible that maneuvers take place in which azimuthal changes occur. Sprint and drift techniques would be an acceptable operational change. The ability to search at night to enable an early morning set is highly desirable.
- The design criteria for school size is 16.5 Ton. It is noted that a commercially productive voyage would have to set on schools of up to 100 Tons, and that schools less than 10 Tons form a lower size limit.
- No one person will be dedicated to sonar operation. The sonar will probably have to inform the fisherman of a contact.
- Any mechanical equipment in the water must be bullet proof if expected to last through the rigors of handling.

Operational Requirements.

A set of operational requirements may be established from these factors which acknowledges the practical aspects of the commercial fishing environment and which limit the capability of the sonar to certain important functions. This sonar design would have the following requirements:

- The sonar doesn’t have to classify the target as a tuna school. Seine boat operation is such that the school will be classified by the fishermen as soon as it is within a 5 to 7 mile radius.
- The sonar must be able to detect a school of tuna at ranges greater than 7 miles. A detection capability out to 10-15 miles would be considered a viable system. If the fisherman was told of a possible contact from 7 to 15 miles away, the boat would be directed there for visual classification.
- Any viable sonar would have to maintain ability to the process signals in beams which are at times slewing through azimuthal changes incurred by maneuvering.
- The sonar would have to look at the volume ahead of the boat, and to either side. There is no need to look aft of broadside.
- School sizes as large as the ones considered commercially important would have target sizes which could reach values 40dB higher than the TS of a single fish. This means that the design calculations could include school TS values which are 5 dB higher than those used in the Rees and Nero reports. To fully bound the problem, the smallest size would be approximately 2 dB smaller than the criterion school size.
- The combined acoustic effects of the tuna boat radiated noise, ambient shipping noise and sea state noise, the non-isotropic nature of the surface sea noise at frequencies above 2500 Hz, and the fall off of the fish hearing response all drive the sonar operational frequency toward 5000 Hertz.
- The signal to noise ratio calculations from open ocean areas, combined with the practical numbers from transducer and hydrophone suppliers, indicate a range of operational frequency from about 3000 to 4000 Hertz for the sonar signal.
- The electromechanical simplicity of a narrowband system is a big advantage when it comes to handling.
- The acoustic discrimination of a system which uses bandwidth is somewhat advantageous in species identification.

The result of this view of the engineering information and the operational requirements leads to a proposed sonar having the following characteristics:

- The operational mode is either a single value about 4000 Hertz, or broadband over a small range near 4000 Hertz.
- The array is a single linear array. If broadband modes are to be used, the design frequency range will be limited to bandwidths which will allow arrays with no nesting. One third octave would be a good design criteria.
- The beamwidth of the receiver array would not be any tighter than 6 to 8 degrees in the horizontal aspect.
- The transmit transducer would be beamformed into a cardioid in the horizontal aspect if size and weight allowed.
- The operator display would be as simple as possible.

Dolphin-Safe Considerations.

Operation of the system should be curtailed at ranges of ~1800m (0.9 nmi) to avoid damage to dolphin hearing. Levels 70 dB above the threshold of hearing (~70 dB at 4 KHz) could impair the animals hearing or affect their behavior.[9] Use of a pulsed system will minimize any effects on the animals. This operating frequency is generally below the dolphin whistle (5-20 KHz) and echolocation (30-130 KHz) frequency range.

Design Objective

The objective of this effort is to develop a system design that fulfills the requirements as initially imposed and derived above. This design should be cost effective, low risk and robust. This should be accomplished via proven design technologies and techniques, and use of Commercial-Off-The-Shelf (COTS) components.

System Concept

The design of a sonar system is presented with the goal to maximize detection of tuna schools at distances greater than 10 nautical miles. The design effort has been driven by the need to maximize use of COTS equipment. The following design description progresses via the subsystems identified in the block diagram shown in Figure 3, below.

The prototype system consists of 3 major components:

- A transmit subsystem: including transmit waveform generation, power amplifier, power supply, projector and handling equipment,
- A receive subsystem: including a towed array defined as sensor package, piezoelectric elements, signal conditioning, Analog to Digital Conversion (A/D or ADC), low noise power supply and multiplexing, and
- A display and control subsystem: consisting of topside computer and interface to entire system and auxiliary equipment.

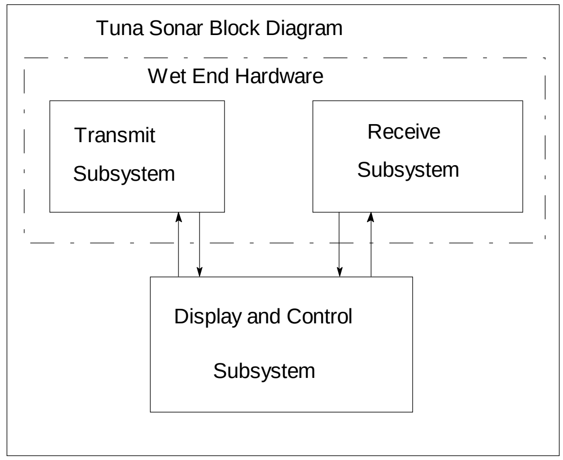

Figure 3 System Block Diagram

The material presented here is a reslult of the design process and a distillation of the information examined. Several features and techniqures that were originally proposed were investigated but rejected for this system because of cost or performance. For example, a vertical receive array provides excellent vertical discrimination against noise, but tows poorly and generates considerable noise when towed, therefore the concept was rejected early in the design process. In another case, a sufficient design was obtained using conventional beamforming techniques and the towed array configuration without resorting to costly (in equipment, software and configuration) noise cancellation procedures. Noise cancellation is an alternative when the physical parameters and propagation effects are relatively stable (ie. hull mounted systems) that is used to some success on submarines.

System Overview

All "wet-end" components are towed via double-wrapped Kevlar® strengthened electrical cables from winches supplied with the system. An alternate scheme of projector deployment is via a leeboard, which eliminates one winch and standardizes the projector depth. A representation of the standard deployed system is shown in Figure 4. One modification of the deployment scheme is that the projector will be attached to the receive tow cable via a zippered fairing to prevent the cables fouling. This addition should also enhance handling[10]. The electro-hydraulic winches are powered via 3-phase 440 VAC supplied from the ship. The system can be mounted on the main deck, starboard side aft of the stack, or on the starboard side of the boat deck.

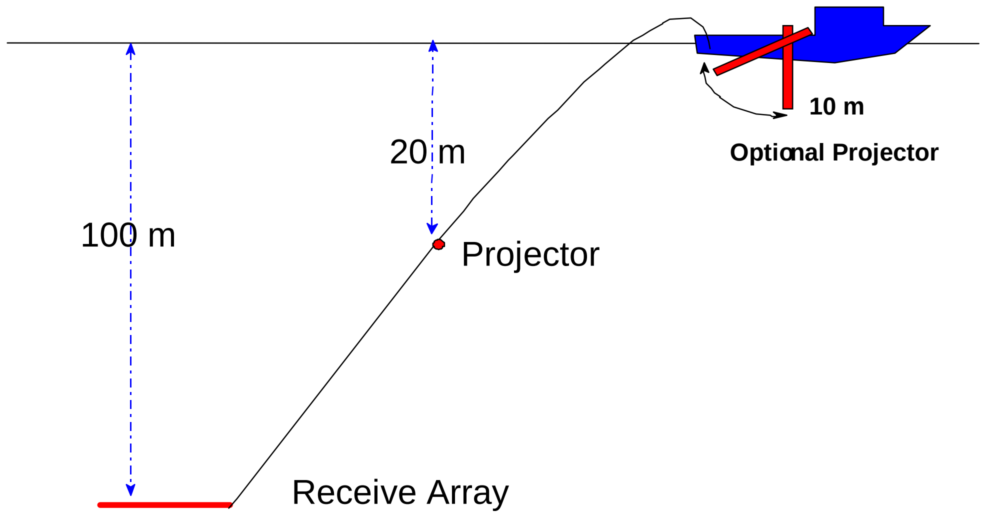

Figure 4 General Tow Configuration

Range gating will be employed to reduce system dynamic range requirements. As there is little interest in contacts inside of 4000m (and dolphin safe considerations would require a 2000m minimum), the system will gate out the first 4000m, and extend to a maximum of 30,000m.

The system achieves 180° coverage via 7 broadband broadside beams (14 with tracking) and the addition of 2 single frequency forward looking endfire beams (3 with tracking, see Figures 6 and 7.) Maximum operational tow speed is anticipated to be 10 knots, with survivability to 15 knots. Employment of sprint and drift techniques (developed by US Navy surface ships in submarine detection exercises) would have the ship cycle a period of time (at least 10 minutes) at 6-8 knots for detection, then sprint ahead at 15 knots to maximize coverage. The system can be deployed at night and in conditions up through Sea State 4 (SS4). An audio alarm will be generated via the topside computer for target detection. An optional interface to display sonar contacts on the radar may assist the operator usage with a single person on the bridge at night. The receive array is towed at a position that minimizes ships noise, and maximizes detection. This location is identified by use of auxiliary sensors indicating array depth, temperature and heading.

A computer located in the array housing will accomplish the beamforming and detection process. This enables a simple low data-rate serial interface with the control and display computer topside. The "wet" computer will receive the conditioned, digitized, and multiplexed signals directly from and at the array to minimize noise and tow cable size. Positioning a computer here allows flexibility, as new programs can be downloaded if modifications are necessary. This enables a simple 3 twisted-shielded pair (TSP) cable with a minimal diameter to reduce fluid dynamic drag and weight.

Operator controls and display are located in the topside computer. This station determines the transmit waveform and ping interval and receives and displays the beam data and auxiliary sensor information from the receive array. Since this is the principal system interface, all diagnostics and data recording are also performed here. Generation of a remote target signal to a NMEA radar interface would also be generated in this device.

A unique feature of the system is a method of exploiting the vertical noise directivity with a horizontal array. We propose using an array element design that looks like the following figure (Figure 5). The array is a series of elements positioned on a pair of Kevlar strength members. Each element has acoustic absorbent material top and bottom to reduce surface and bottom reflected energy, leaving open the horizontal area. It is anticipated that this readily available material is adequate for at least 10 dB and potentially 30 dB of sound reduction broadband. Performance requirements will require testing of materials to assure the 30 dB reduction in the narrower 3-4 KHz band. Using this method forces a requirement on the array for roll stability, however this is a minor feature that has several solutions in the tow body design (stablizer fins and attachment point mechanics) and in the use of a urethane potted (vice oil filled) array.

Noise is expected to have a significant impact on performance. Via the sonar equation, with all other factors kept constant, increased noise translates into decreased performance (ie. decreased detection ranges). The impact of noise reduction on performance can be examined to a first approximation in system range as a function of both TS and noise level. In Table 1, noise is shown as both Sea State level, or an additive noise above the SS0 starting point to impart the effects of in-band noise from any source (e.g. flow noise, ship-borne noise, position of the array in the ship's noise field, etc.), with ranges calculated using the criterion school size of 16.5 Ton (TS = 0 dB). To indicate the Sea State condition, wind speed and wave height are also shown in the table. The use of the table is in understanding relative changes, as the actual propagation is not a smooth linear function in range. Flow noise is difficult to predict, as it is often a function of the combination of materials used, the finish of the process, the frequency of generated noise relative to the bandwidth of operation and the location of the array in flow turbulence. Self noise is a continuing problem on any vessel, as conditions of paint, plant and animal incrustations and collisions continually modify the flow characteristics and influence the performance of any sonar system It is an item requiring periodic monitoring.

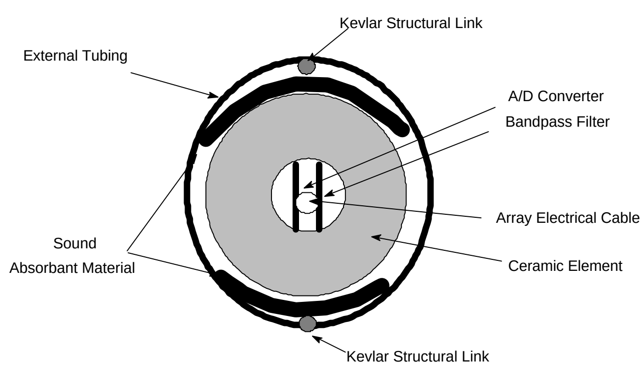

Figure 5. Array Element Configuration

Table 1. Dependency of Range on Noise and Target Strength.

Avgerage Wind	Average Wave hgt	Ambient Noise	Change in Noise level	Size (T):	10	16.5	100
Knots	ft: avg/hi	dB	dB	TS:	-2	0.0	8.0
				Sea State			
0-2	0/.1	34	0	0	28.1 Km	30 Km	39.2 Km
4-7	.3/.37	44	+10	1	19.3 Km	21.0 Km	28.1 Km
10-12	1/1.2	50	+16	2	15.1 Km	16.0 Km	22.5 Km
12-16	2.9/3.7	54	+20	3	13.0 Km	13.7 Km	19.3 Km
17-20	6.9/8.7	56	+22	4	11.6 Km	13.0 Km	17.1 Km
20-24	10/13	58	+24	5	11.2 Km	11.5 Km	16.2 Km

Changes in TS between -2 and +8 dB are equivalent to the changes in range between SS0 and SS1 noise levels, thus large targets can be expected to be detected at much greater ranges than small ones.

For another view of expected range, examination of the Rees report on transmission loss can be made using a 1-way transmission loss of 78 dB (SS3, TS = 0 dB) extrapolated between the 2 KHz and 5 KHz frequncies. Depending on region, season and target depth, non-continuous modeled ranges from 5 Km to in excess of 40 Km can be obtained for the single value of TL.

(MATLAB generated full-page graph to be put here)

Figure 6. Receive Beam Structure at 4 KHz

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Figure 7. Receive Beam Structure at 3 KHz

Transmitting Subsystem

Low frequency projectors tend to be expensive due to the size necessary to obtain reasonable source levels with large wavelengths. Therefore, a particular driver of a low-cost system is a COTS projector close to the desired frequency range. In addition to adequate transducer performance, there is also a requirement to be able to drive the projector. After adding a transformer to the transducer to achieve sufficient drive voltage, the output impedence seen by the power amplifier (PA) often varies wildly between inductive and capacitive loads even over narrow frequency ranges. More than a transducer, the critical component is a transducer and PA combination. Rees' work indicated a minimum source level of 185 dB would be required, with 200 dB being preferable. We propose using an existing design transducer capable of 196 dB in our operating band, coupled with a PA known to drive highly reactive acoustic loads with great reliability. Both of the firms that produce these devices have been in business for over 50 years. Figure 8 displays a functional block diagram of the subsystem.

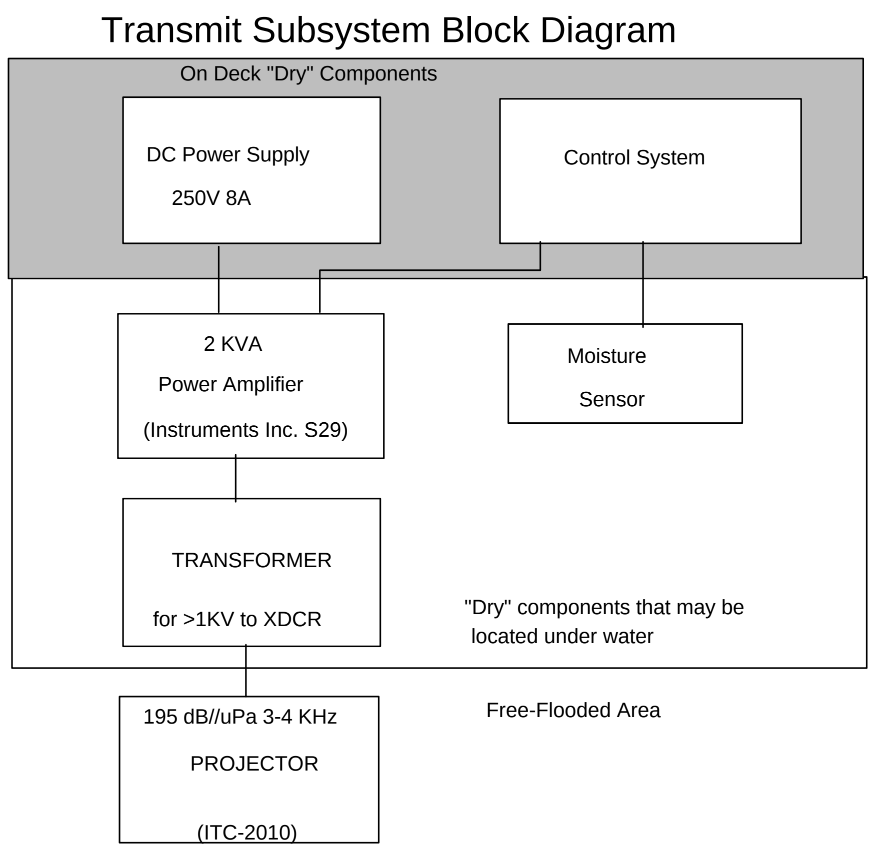

Figure 8 Transmitting Functional Block Diagram

Projector Description

The basic characteristics of the projector can be satisfied by several devises by different manufacturers. We have focused on one particular device as it not only meets the basic criteria, but also allows the potential of expanding the broadband capability in the future, and is a cost effective solution. This device is the ITC-2010 by International Transducer Corp. The stock model (in PZT-4) will produce at least 192 dB at 3200 Hz with 1000 VA applied. This level can be increased, for a minor additional cost, by 4 dB with the use of PZT-8 material, allowing 2 KVA to be applied, which increases the Transmit Voltage Response (TVR) to at least 196 dB//μPa @ 1m. The transducer is free-flooded in a cylindrical format

(12.9” x 16.6”) and weighs ~74 lbs in air, 30.8 lbs in water. It has no horizontal directivity, and about 4 dB vertical directivity in the 3-4 KHz region. A reflective wedge may be placed immediately aft of the transducer to render some horizontal directivity into the forward ½-plane without damaging the projector.[11] This addition may give up to 3 dB more signal in the area most needed, giving a source level of 197-199 dB and at a cost of ~$15,000 in single quantities.

Power Amplifier Description

The Power Amplifier (PA) to drive this type of transducer will need to drive an impedance varying from 5000Ω to 5Ω (capacitive) and at voltages up to 1750VAC. Two types of amplifiers are available for this task: linear and switcher. Linear amps are typically class A type, similar to stereo amplifiers, that boost the signal with little distortion. The down-side is the size and weight of the transformers required in these devices make them unwieldy. Switcher amps now operate at 200 KHz to breakup the input waveform and amplify the segments. These amps have limited frequency range but offer great savings in size, weight and cost. The frequency range of our system is well within the range of most switchers. If we assume a power factor of 2 on a noise drive signal, we would need ~4KVA in PAs for this design. Instruments, Inc., a well known manufacturer of PAs for use with transducers, produces 1KVA boards (6” x 12-14”, model S29) that would easily operate in the difficult impedance regime of the transducer. They run on 250 VDC and would require a transformer for voltages in excess of 1000V. This design would require 4 board sets, at a cost ~$3400 each (list, up to 25% discount available for quantities[12].) Additionally, there is a requirement for a 250 VDC P/S (< $3K, can get via Inst., Inc.) somewhere onboard the ship and a cable capable of 8A, continuous power. Mounting of the PAs can be anywhere on deck or just above the transducer. We propose a standard practice of mounting the PAs and transformer in a sealed compartment immediately above the transducer, minimizing lead lengths of high voltage and noise coupling into the transducer. Cooling of the amplifiers is also facilitated by this placement. A sketch of this arrangement can be found in Figure 9, below.

Tow Body and Cable

The tow cable has 2 primary constraints: it must handle the power (250V, 8A) and provide a strength sufficient to withstand the weight and drag of the cable and towbody at speeds up to 15 knots. The drag of electronics body can be expected to dominate cable tension with the free-flooded transducer at ~36 lbs., and the PA housing at or less than that weight. The cable tension is:

$$T = F_{Weight} + F_{Drag}$$
$$= 75 + \tfrac{1}{2} C_D V^2 A\rho \text{ lbs.}$$

where C_D is the drag coefficient, A the area and ρ is the density of the fluid

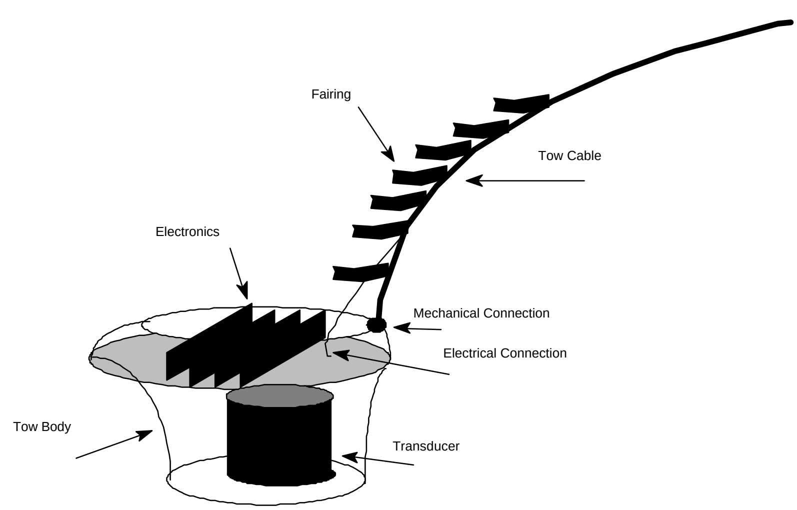

Figure 9 Towed Projector configuration

Since drag is a function of the velocity squared, there is a dramatic increase in line tension with speed. Figure 10 shows the graph for this system with 50m cable out. Note that the slope changes at the upper speed end because of a drag crisis with the change in Reynolds numbers near 10^5, which reduces the drag coefficient from .63 to .35. The upper limit of survivability arises from this calculation for the cable. The cable selected has a working strength of 1000 lbs, with a breaking strength of 8000 lbs. The strength member is a counterbalanced double wind Kevlar strand. The aramid fiber has tensile strength of approximately that of steel, and approximately 1/10 the

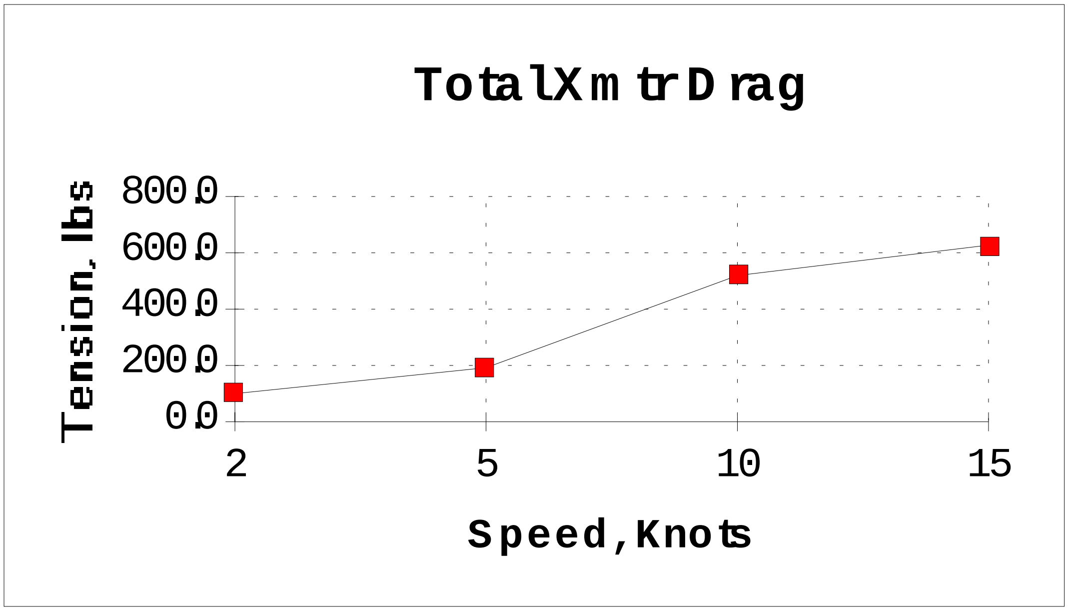

Figure 10 Transmitter Drag Plot

weight. The cable is sheathed in a polyurethane coating, to provide water-tight integrity and protection for sunlight, as Kevlar rapidly looses strength when exposed to ultraviolet radiation.

An alternate deployment plan would have the transmitter placed on the bottom of a leeboard which would swing into place. This would remove the strength requirement on the cable. The transmitter would be fixed at a 10m depth which would simplify deployment and the winch. Consultation with a Naval Architect would be required regarding this design change to assure proper strength of the board and it's affect on the handling characteristics of the ship.

Transmit Waveforms

Three fundamental waveforms will be utilized in this system:

- Pseudo-random sequence (similar to a Barker Code),
- Frequency Modulated (FM) sweep (Chirp)
- Continuous Wave (CW) single frequency

In the standard mode of operation, alternate pulses would be CW (for the forward look) and a broadband (Chirp or random sequence) pulse for the broadside beams. This combination allows more bandwidth for identification purposes where the beams are controllable, and a single frequency for the endfire condition which is not tolerant of off frequency components.

Receiving Subsystem

The receiving subsystem is broken into functional groups: elements, signal conditioning, digitizing, multiplexing, beamforming and array hardware (including cable.) The component specifications and design criteria to determine the specifications are provided

Array Elements

The towed array for the sonar will have the necessary beam size characteristic if it is configured as a linear array with element spacing of ½ wavelength ($\lambda/2$)at 4000 Hertz (see Figures 6 and 7 for beampatterns.) The array will be about nineteen feet long. A number of undersea hydrophone elements were considered for the task. All of the hydrophones considered possessed about the same acoustic sensitivity. The one chosen for calculations to support the wet end design is an ITC-1010 A acceleration canceling towed array element. This element has the following engineering characteristics:

Sensitivity:	- 186 dB re: 1 V_{RMS} / μPa
Nominal Capacitance:	.002 microFarad (μF)
Horizontal Beam Pattern:	Omni $\pm$ 0.5 dB to 2 KHz
Vertical Beam Pattern:	Omni $\pm$ 1 dB to 2 KHz
Depth Capability:	Unlimited
Physical Size:	4.4 inch long, 3.5 inch diameter

The size of the element is in keeping with other packaging characteristics which drive the system design. The element has a history use in towed array systems, and is widely accepted as a good low frequency sensor. The acceleration canceling design is a positive attribute for a sonar system destined for a vessel with little or no experience with towed acoustic arrays.

<u>Hydrophone Response to Ambient Noise:</u> The sonar design has assumed a Knudsen sea state value of SS0 for the calculation of all sonar detection and detectability criteria. This is important to establish the minimum signal level and maximum amplifier gain necessary for the system. The following calculations of hydrophone output voltage will be used to establish the signal conditioning parameters for the sonar front end electronics:

Sensitivity:	- 186 dB re: 1 V_{RMS} / uPa
Bandwidth:	4000 Hertz
SS0 acoustic noise:	34 dB_{SPL} re: 1 V_{RMS} /$\sqrt{Hz}$

The open circuit voltage from the hydrophone element when in the specified noise field is as follows:

$$E_{OUT} = -186\ dB + 34\ dB_{SPL} + 10\log_{10}(4000\ Hz)$$
$$E_{OUT} = -116\ dBV_{RMS}$$

<u>Hydrophone Response to Return Echo:</u> The return echo from the 10 ton and 100 ton tuna schools is calculated using the following parameters:

- Sonar Source Level, SL: +196 dB_{SPL} re: 1 μPa @ 1m
- 10 ton school, TS_{10}: -2 dB
- 16.5 ton school, TS_{16}: 0 dB
- 100 ton school, TS_{100}: + 8 dB
- Shortest sonar range, R_S: 4,000m
- Longest sonar range, R_L: 30,000m

In order to determine the maximum dynamic range of the system, the cases that become important to the front end design are: the return echo strength from the largest target at the shortest range, and from the smallest target at the longest range. The Sonar equation provides the following results:

$$\text{Echo} = \text{SL} - 2\text{TL} + \text{TS} \qquad \text{where TL} = 20 \log_{10} R$$

$$\text{Echo}_{100} \ @\ R_S = 196 \text{ dB} - 2(20 \log_{10} 4{,}000) + 8 \text{ dB}$$
$$\text{Echo}_{100} \ @\ R_S = 60 \text{ dB}_{SPL} \text{ re: } 1\ \mu\text{Pa} \ @\ 1\text{m}$$

$$\text{Echo}_{10} \ @\ R_L = 196 \text{ dB} - 2(20 \log_{10} 30{,}000) - 2 \text{ dB}$$
$$\text{Echo}_{10} \ @\ R_L = 15 \text{ dB}_{SPL} \text{ re: } 1\ \mu\text{Pa} \ @\ 1\text{m}$$

The open circuit voltage from the hydrophone element when in the specified echo return field is as follows:

$$E_{OUT} \ @\ R_S = - 186 \text{ dB} + 60 \text{ dB}_{SPL}$$
$$E_{OUT} \ @\ R_S = - 126 \text{ dBV}_{RMS}$$

$$E_{OUT} \ @\ R_L = - 186 \text{ dB} + 15 \text{ dB}_{SPL}$$
$$E_{OUT} \ @\ R_L = - 171 \text{ dBV}_{RMS}$$

Thus the necessary dynamic range is from -126 to -171 dB, a difference of 45 dB.

Signal Conditioning

The noise field and signal field values indicate that the available signal to noise ratio is not sufficient for omnidirectional sensors. Array gain will be required. Two methods will be used to achieve that end: physical shading for vertical discrimination, and a phased array for horizontal discrimination. One aspect of the noise field measured in very deep water, away from continental influences, is a beam pattern structure. This structure, illustrated in Figure 2, allows significant discrimination against the sea surface generated noise which dominates the frequency region we will use for the sonar. Physical shading of the individual elements (Figure 5) in the array such that sound from depression angles less than - 30 degrees and greater + 30 degrees may provide upwards of 30 dB of noise reduction. The array itself will possess a directivity index of about 11 dB, adding to the total array gain.

For the purposes of the conceptual design of the tuna sonar front end electronics, we now have the bounds of the estimated signal set. The sonar concept includes two independent modes of operation which will take advantage of different characteristics of the beamformed array. A broad band technique will be used to detect and possibly classify tuna schools in the narrower beams of the array. This system will be about 1000 Hertz wide, and will have a short enough transmit pulse to allow range resolution in the order of 100 feet (30 m). Signal to noise ratio in the acoustic fields will limit this technique to the narrower beams of the array. The broad, nearly 55 degree end fire beam, will not provide enough discrimination against noise to be used with a 1000 Hertz wide receiver bandwidth, nor can the broadband array be steered to endfire.

A narrow band sonar technique will be used to detect tuna schools in the forward looking end fire beam and the two beams adjacent to end fire. This technique will not allow classification of the target as tuna, however, the information that a tuna school is possibly ahead is considered worth the inclusion of the detection only system. A functional block diagram of the conceptual front end is shown below in Figure 11.

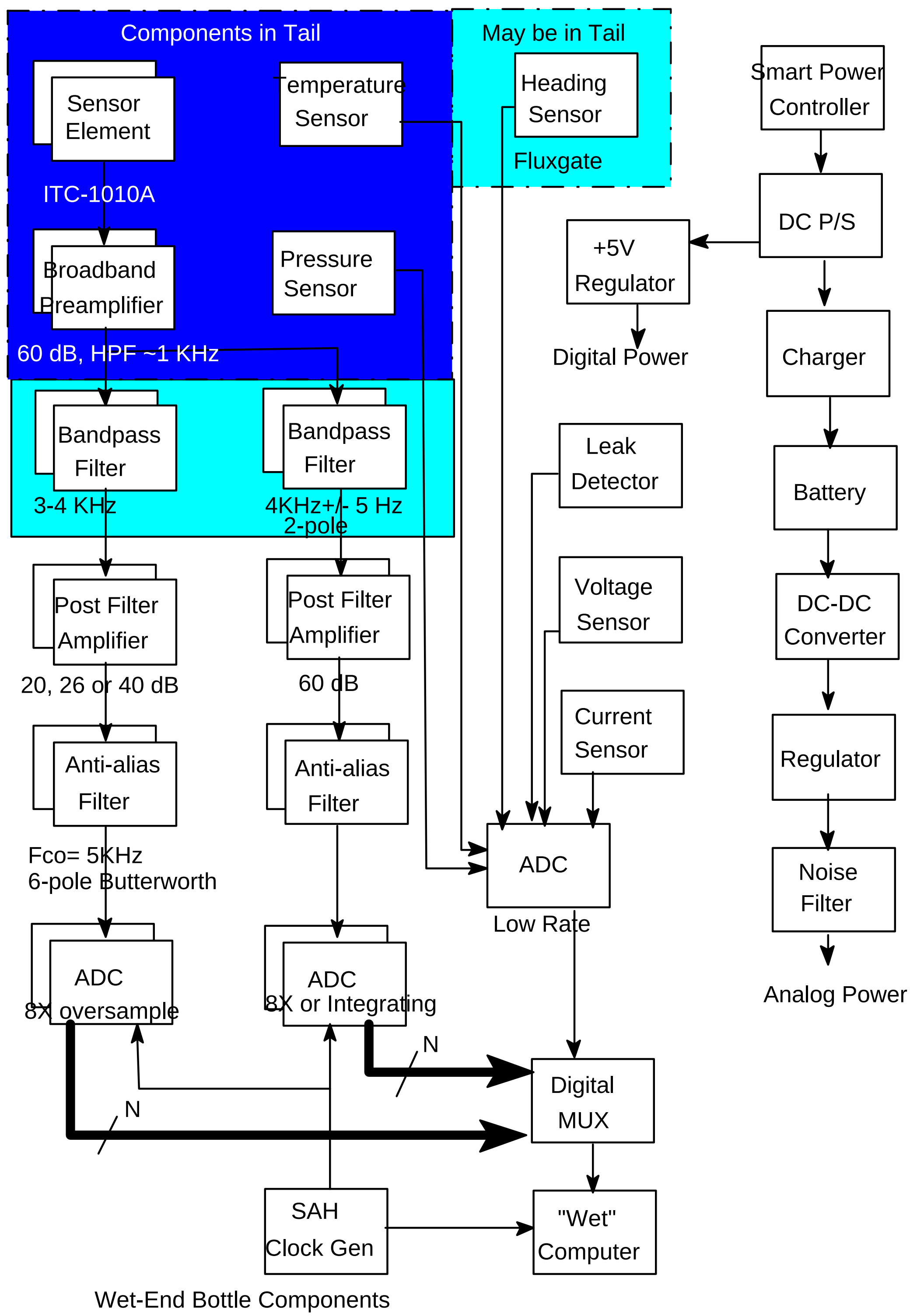

Figure 11 Receive Subsystem Functional Block Diagram

Critical Engineering Design Calculations.

The engineering design calculations will proceed thorough the functional block diagram from the analog to digital converter block back to the hydrophone element block. The individual steps will be as follows:

- Sampling Speed Discussion: The rate at which the acoustic information is time sampled, and the engineering significance of the data rate will lead to a choice of conversion technique.
- Analog To Digital Converter Discussion: The value of the bit size of the conversion and dynamic range of the acoustic information will lead to the required input voltage for proper acquisition of the sonar signal set.
- Antialias Filter Discussion: The analog sampling speed and the digitization size will lead to the requirement for rejection of alias frequency components. The resultant filter requirements will be satisfied with electrically realizable component technology.
- Amplifier Gain and Filtering Discussion: The signal voltage available from the proposed hydrophones, and the input voltage range requirement of the analog to digital converter, will lead to determination of the voltage gain necessary in the broadband and narrowband paths of the analog signal conditioning electronics. High pass and band pass filtering techniques will be applied to the signal conditioning paths as required.

Sampling Speed Discussion

The rate at which the analog signal is sampled is driven by the fastest excursion of the voltage waveform, and by the needs of the signal processing system for sufficient over-sampling in the time domain. The fastest voltage waveform excursion for the sonar signal set will be a 4000 Hertz sinusoidal waveform. It is convenient for the signal processor design to over-sampling by 8 times for beamforming of the acoustic data.

The proposed towed sensor is a linear spaced ($\lambda/2$), 19 element (Hanning shaded) array with a design frequency of 4000 Hertz. The temporal period of the 4000 Hertz waveform is:

Period = 1 / 4000 = 250 microseconds

The Nyquist theorem requires that the waveform be time sampled twice this fast:

$S_{NYQUIST}$ = 250 / 2 = 125 microseconds per sample

The 8 times over-sampling for the digital signal processor leads to the following sampling speed:

$S_{8X\ over}$ = 125 / 8 = 15.6 microseconds per sample

The sampling speed calculated above results in a sampling frequency as follows:

$F_{S\ 8X} = 1 / 15.6 \times 10^{-6}$ = 64 KSPS

The design may be implemented with one analog to digital converter per element, or may be implemented with one analog to digital converter per array. The former choice may be satisfied with a converter equivalent to the Burr Brown ADC 774. This unit has the following basic specifications:

Conversion Size:	12 bit
Sampling Frequency:	117 KSPS maximum
Input Range:	± 10 Volts

This converter also has internal sampling circuitry, thereby eliminating the need for this design step.

If the design is implemented with a single analog to digital converter for the entire array, the sampling requirements grow by a factor of 19 to cover all of the elements. The sampling rate now increases as shown:

$S_{19\ Element} = 15.6 / 19 = 822$ nanoseconds per sample

The sampling speed calculated above results in a sampling frequency as follows:

$F_{19\ Element} = 1 / 822 \times 10^{-9} = 1.216$ MSPS

The specification of this signal acquisition technique may be satisfied with a converter equivalent to the Texas Instruments TLC 876. This unit has the following basic specifications:

Conversion Size:	10 bit
Sampling Frequency:	20 MSPS maximum
Input Range:	+ 5 Volts

This unit does not supply any sampling electronics. The sample and hold function would be up to the designer. Using the device would also require the designer to provide DC level shift circuitry to place the bipolar sonar signals into a zero to five volt input range.

A number of factors lead to the choice of implementing the design with an ADC on each element for each of the two modes of operation of the sonar. A summary of these factors is as follows:

- Analog to digital converters with higher conversion sizes are more readily available at reasonable cost when the conversion speed is lower.
- ADC's with internal sampling require less design effort in the low noise, analog electronics.
- The ADC's with larger conversion sizes, although not needed to adequately digitize the signal set in question, will provide more of the noise signal to the digital signal processor. This will be of benefit in the discreet Fourier transforms employed by the broad band sonar technique.
- The reliability of a sonar implemented with one ADC for each element for each of the two modes, is enhanced by the fact the loss of a single ADC will only remove the contribution of one element to the operation of one of the modes of the sonar. The degradation of the beam structure in the failed mode may not be severe. The second mode of operation will be unaffected.
- The loss of one ADC in a sonar implemented with a converter per array mode will result in the total loss of that mode.
- The use of a single ADC for multiple analog signals invokes the design of analog signal multiplexing. The use of multiple ADC's, one per analog signal, invokes the design of digital signal multiplexing. Digital signal multiplexing is inherently quieter than analog signal multiplexing.

The proposed implementation will be to provide each array element with two ADC's. The broadband signal acquisition path will use an ADC equivalent to the Burr Brown ADC 774. The path for the narrow band sonar would be more than satisfied with the same ADC, however, the lower data rate expected in this sonar mode, and the absence of need for DFT processing may relax the requirement for over-sampling enough to choose a slower ADC. The cost differential, however, is not great enough to overcome the necessity to specify the higher rejection antialias filter that would be required by the 4 times sampling speed. The proposed implementation will be to put the same Burr Brown ADS 774, or equivalent ADC on each element for the narrowband sonar.

Analog to Digital Converter Discussion

The conversion size of the ADC's, 12 bits in both cases, and the input voltage range ADC analog circuitry must be matched to the dynamic range of the acoustic information provided by array electronics. The following engineering calculations provide the necessary information to establish ADC input requirements.

The ADC input voltage range is plus and minus 10 Volts. The value of the sonar signals will be described in ac Volts RMS, or in dB re: 1 V_{RMS} requiring that we convert ADC input voltage specifications to RMS.

$E_{IN\ ADC} = \pm 10$ Volts $= 20$ Volts $_{PEAK\ to\ PEAK}$
$E_{IN\ ADC} = .3535 \times 20_{\ PEAK\ to\ PEAK} = 7.07\ V_{RMS}$
$E_{IN\ ADC} = 20 \log_{10} (7.07\ V_{RMS}) = 17\ dBV_{RMS}$

The conversion size of both ADC's is 12 bit. At 6 dB per bit, the conversion size expressed in decibels is 72 dB. The largest signal expected from the array is the echo return from the larger target size school, at the closest design range. This signal level was calculated to be 60 dB_{SPL} for our sonar. The smallest signal expected from the array is the echo from the smaller target size school, at the farthest design range. 17 dB_{SPL} was the result of this calculation. We can now place the sonar signal set within the ADC conversion range to ensure that sufficient conversion is available.

The dynamic range of the sonar signal set is as follows:

$E_{\ Dynamic\ Range} = 60\ dB_{SPL} - 17\ dB_{SPL} = 43$ dB

The signal will be placed in the 72 dB conversion range of the ADC's in accordance with the following table:

ADC Input Signal	SPL	Input dBV_{RMS}	Bit
Overhead allowance, 1 Bit		+17 dBV	MSB
Maximum Sonar Signal	60 dB_{SPL}	+11 dBV	Bit 11
		+5 dBV	Bit 10
		- 1 dBV	Bit 9
		- 7 dBV	Bit 8
		- 13 dBV	Bit 7
		- 19 dBV	Bit 6
		- 25 dBV	Bit 5
		- 31 dBV	Bit 4
Below Minimum Sonar Signal	12 dB_{SPL}	- 37 dBV	Bit 3
		- 43 dBV	Bit 2
		- 49 dBV	LSB

The table indicates that adequate conversion size exists for the expected signal, and that the bottom 2 bits will contain noise for the digital signal processor Fourier transform.

Antialias Filter Discussion

The analog sampling speed of 64,000 samples per second will accurately describe AC voltage waveforms with components up to 32 KHz. Above this frequency, alias terms will be created by the sampling process. A filter designed to attenuate a full scale, 17 dBV_{RMS} input at 32 KHz to a level which cannot toggle the LSB of the ADC would have to provide 72 dB of attenuation at 32 KHz. The same filter would have to pass a full scale, 17 dBV_{RMS} input at 4 KHz without any attenuation so that the desired sonar signal is applied to the ADC unaltered. In order to ensure proper rejection, the requirement for the antialias filter will be specified to apply an additional 6 dB attenuation at 32 KHz. The result of this is a filter which slopes from zero attenuation at 4 KHz to 78 dB attenuation at 32 KHz. Specification of a readily realizable 6-pole Butterworth Low Pass Filter will provide attenuation well in excess of 78 dB in the required frequency range. The excess is, in fact large enough to allow placing the cutoff frequency at 5 KHz. This specification will improve the phase response of the filter at the 4 KHz design frequency. The following plot (Figure 12) illustrates the filter amplitude characteristics.

Amplifier Gain and Filtering Discussion

The remaining functional blocks in the signal conditioning and acquisition paths of both sonar modes deal with the voltage amplification of the noise and sonar signals from the undersea hydrophones in the array. The paths are shown with amplification just after the element, filtering to condition the amplified voltage, and post filter amplification just ahead of the anti alias filter. The application of voltage gain in two stages has been specified for the following reasons:

- The required voltage gain to condition the hydrophone output to a value consistent with the ADC input range is high enough to require that more than one amplifier be used. Application of much more that 70 dB of non inverting voltage gain using one amplifier is risky in terms of amplifier stability.

- The requirement for bandpass filtering is different for each of the sonar modes. The broadband mode requires a broadband filter, the narrowband mode does not.
- Two stages allows a single amplifier, with appropriate buffered outputs, to be used to drive both of the bandpass filters.
- A single, high gain stage physically located within the array, on top of the element, will eliminate the signal losses associated with longer cable runs from the high impedance elements into the electronics bottle. The degradation of acoustic hydrophone sensitivity avoided could be as high as 2 dB per element.
- The two different sonar modes will require two different gains in second stages of voltage amplification.

The calculations of gain and filtering for the broadband sonar mode will be presented first. The echo level from the largest target size school at the closest range, as calculated earlier, is as follows:

E_{OUT} @ R_S = - 126 dBV_{RMS}

The desired voltage for this signal, when applied to the ADC input is as shown in the ADC Table, and as follows:

Maximum Sonar Signal: +11 dBV_{RMS}

The required voltage gain is the difference between the two voltages as follows:

VA = +11 dB - (- 126 dB) = 137 dB VA

Reserved for Bode Plot

Figure 12 Bode Plot of Filter Response

This is a significant amount of unfiltered gain. A reasonable approach at this point is to apply this gain to the expected noise signal to see the result. The Knudsen SS0 noise values, as calculated earlier will result in an open circuit voltage from the hydrophone of -116 dBV_{RMS}. If +137 dB of unfiltered voltage gain is applied to this signal, the resultant output voltage would over scale the ADC. Some type of filtering is necessary on the first amplifier stage to reduce the noise voltage. Reducing the bandwidth of the first stage to 1 KHz by application of a single pole, high pass frequency response to the amplifier will change the equation as follows:

$$E_{OUT} = -186\text{ dB} + 34\text{ dB}_{SPL} + 10\log_{10}(1000\text{ Hz})$$
$$E_{OUT} = -122\text{ dBV}_{RMS}$$

This result takes us a little closer to a value within the ADC conversion range, however it is still too large when compared to the expected signal from the target echoes. We must now apply the significant reduction of noise which is predicted if the vertical beam structure of the surface generated noise field can be taken advantage of by applying attenuation in the form of reflection or absorption above and below the hydrophone. If the interpretation of the vertical structure plot, as shown below, is conservative, the possible array gain resultant from physically shading the element is upwards of 30 dB. If we assume this level, the noise equation changes as follows:

$$E_{OUT} = -186\text{ dB} + 34\text{ dB}_{SPL} + 10\log_{10}(1000\text{ Hz}) + 30\text{ dB}_{AG}$$
$$E_{OUT} = -92\text{ dBV}_{RMS}$$

As a second attempt to determine the overall voltage gain, let us place the noise level calculated above into the bit position we would like to have the smallest expected echo signal. The echo level from the smallest target size school at the farthest range, as calculated earlier, is -169 $dBV_{RMS.}$ The desired voltage for this signal, when applied to the ADC input is as shown in the ADC Table, and is:

Below Minimum Sonar Signal: -37 dBV_{RMS}

The required voltage gain is the difference between the two voltages is:

VA = -37 dB - (- 169 dB) = 132 dB VA

The value comes out within 6 dB VA of the gain calculated for the largest signal case. It is proposed that the first stage of the sonar, that amplifier which will be located with the element in the sensor array, be specified to have 70 dB VA of voltage gain, and to include components for a one pole high pass response with a cutoff frequency of about 3 KHz.

The band pass filter which follows the first stage for the broad band path will be specified to have a one pole response on both sides of the filter, and an in band voltage gain of 20 dB. The amplification stage which follows the filter is usually configured to have gain control. It is proposed that this stage be controlled over a gain range in three steps of 20 dB, 30 dB and 40 dB. The control will be possible with a 2 bit command.

The narrowband mode of the sonar will use the same first stage of amplification. The bandpass filter which follows this stage may be much narrower, however. Since the narrowband mode will be expected to use a long, nearly 1000 millisecond, sonar ping, the band width of the filter can be very narrow. The stage is proposed to have a bandwidth of 10 Hertz. This will once again reduce the noise voltage which reaches the ADC. This will change the equation as follows:

$$E_{OUT} = -186\text{ dB} + 34\text{ dB}_{SPL} + 10\log_{10}(10\text{ Hz}) + 30\text{ dB}_{AG}$$
$$E_{OUT} = -112\text{ dBV}_{RMS}$$

The reduction of the noise value will not require any change in the overall gain because the expected target returns are still the same. The advantage however is realized when the target is at great distances. The overall noise is reduced, therefore the range of detection is increased. It is proposed that the controllable gain stage in the narrowband path be configured with the same three step control, but that the gain values be 26 dB, 36 dB and 46 dB.

Array Power

Power to the analog circuitry is supplied via on-board Ni-Cad batteries (see Figure 11.) The necessary DC levels are developed using a DC-DC converter with an on-chip regulator. A simple low-pass filter preserves the noise-less atmosphere required for SS0 operations. Digital potentials are derived via DC-DC conversion of a level supplied from the topside power supply. The levels required to run the computer are kept separate from the analog levels to minimize noise contamination. The Ni-Cad pack will be recharged via the topside power supply and in-water regulator system

Tow Body and Cable

Figure 13 show a typical towed array configuration. The cable is a 6 TSP (.63" diameter) configuration with the lower ½ faired to cut fluid drag. The front housing will contain the attachment point and electrical connectors. The housing is larger than the array to house the multiplexer (MUX) and computer, and the power condition segments. The array itself is potted in urethane for ruggedness. The after tow element is for fluid dynamic stability. The lead body will contain depressor wings to "fly" the array to a scope of <2 to minimize cable and to move the array out of the "noise plume" of the ship's propeller (observed in the sample in Rees' report.)

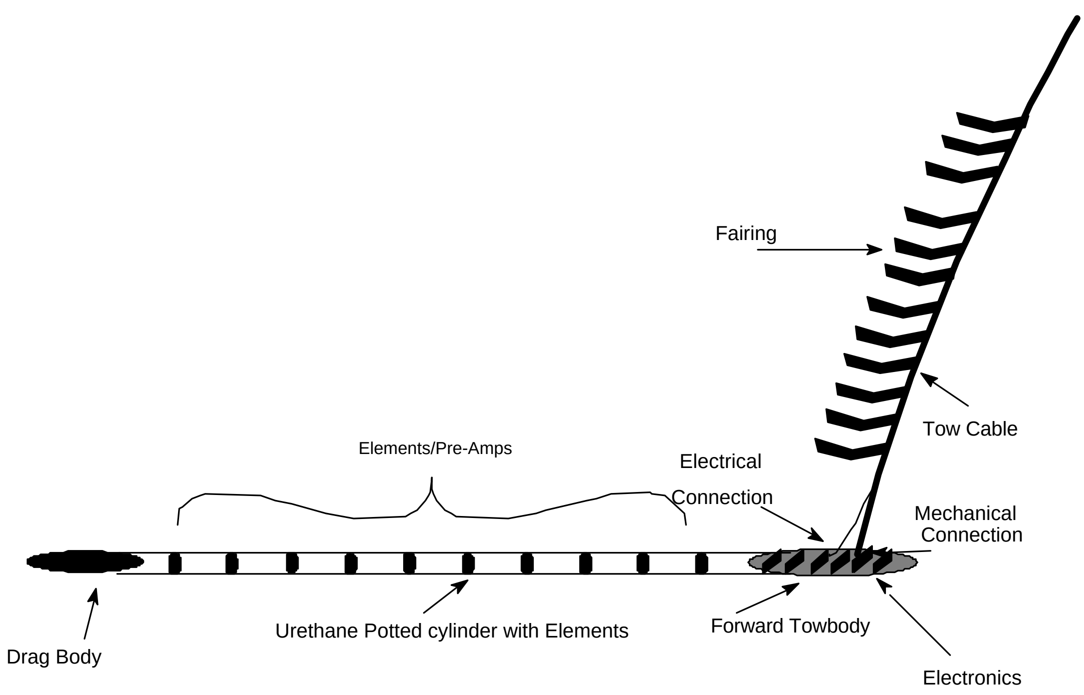

Figure 13 Receive Towed Array Configuration

Processing Subsystem

This subsystem performs the tasks of operator interface and data analysis, including detection tracking, and localization. It will be implemented in software on 2 processors in the system, shown in the following Figure 14.

Requirements

The processing requirements revolve around 2 fundamental areas: beamforming and data display. As this system is divided, each area will involve a separate CPU in separate locations. Inter-computer exchange is to be via standard serial interface. The topside display computer will be the control device with the capability of sending new instructions to the beamforming CPU.

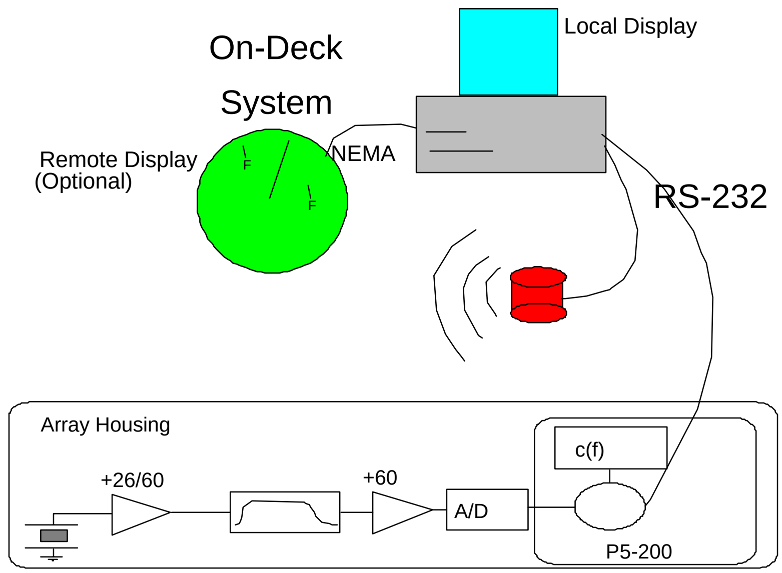

Figure 14 Processor Operations

Beamforming is done via a set of standard operations:

- Multiply Hanning shading weights,
- Sum the array element outputs, and
- For broadband, apply DFT to data to get frequency dependent information.

The processor will have to accept the inputs, and condition the outputs in the following table:

Output	Input
Transmit Waveform	Auxiliary Sensors
Local Display	Receive Beam Data
Mode Control	
Remote Display Generation	

Software Description

There is no inherent restriction on either language or operating system in the development of the software for this sonar. SciFish plans to develop this software to maximize use of existing working code. A corporate decision has been made to develop software in the Microsoft Windows 95 operating system using Visual Basic.

In the following software flow diagram (Figure 15), the computational load is split between the "wet" and "dry" computers for both convenience of function and reduction of wires between the 2 environments. The split reduces the communication to conveyance of commands down line, and beam numbers up line at rates less than 100 words per second (~3200 Baud.) Sensor information will be updated at a once/second/sensor rate. The beamforming and leveling operations will occur in the "wet" end, while the operator interface and data storage will occur on the "dry" end.

Standard tracking algorithms will be required to resolve the left-right ambiguity of the towed array and provide target track and localization data. Tracking will operate with both CW and BB pulses. Track data can assist classification and reduce false alarms. Target data will only be stored on specific operator command. At that time, the data structure will incorporate all environmental and position data into a database as well as signature and track data. This feature is intended for training of both personnel and neural networks on validated signatures. This will be implemented on the topside computer as part of the display program.

Identification will result from the accumulated knowledge of acoustic signatures, environmental data, tracking data and visual inputs via neural networks. The software will “learn” the combinations of attributes that signify a detection and respond with an appropriate alarm to the operator. Schools of tuna without the attributes of dolphins are to have a separate alarm.

Storage of target information will be at the discretion of the operator. In the prototype system, all target information will be stored to a floptical disk in a database to include operating conditions and geographical information. As data becomes available on the particular target, ie. identification of species, size and sex distribution and any other knowledge such as helo observations of packing density, that data is also included in the database. It is anticipated that only minimal information will be stored in an operational system, such as catch distribution with GIS data. Such software already exists in SciFish’s Fishermans Associate.

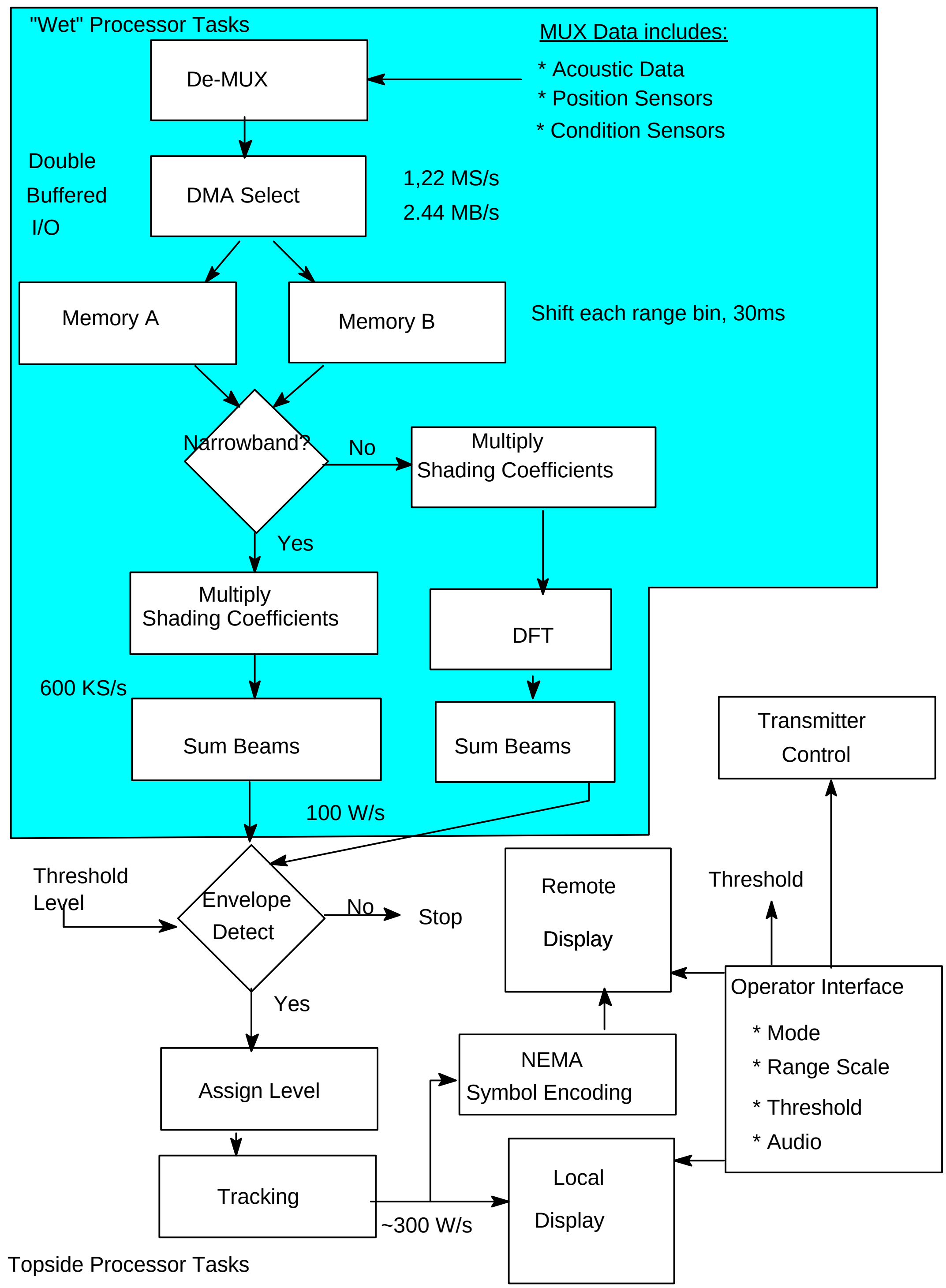

Figure 15 Software Functional Flow Diagram

Display

The primary display of the prototype system will be on the topside computer. The system will need to generate at least one display for the topside computer, including an audio alarm for the ship's crew. An optional display will be generated in the future to send contact data to the radar display as symbols.

Local Display

The local display will include the operator commands, beam data and auxiliary sensor data similar to that in Figure 16.

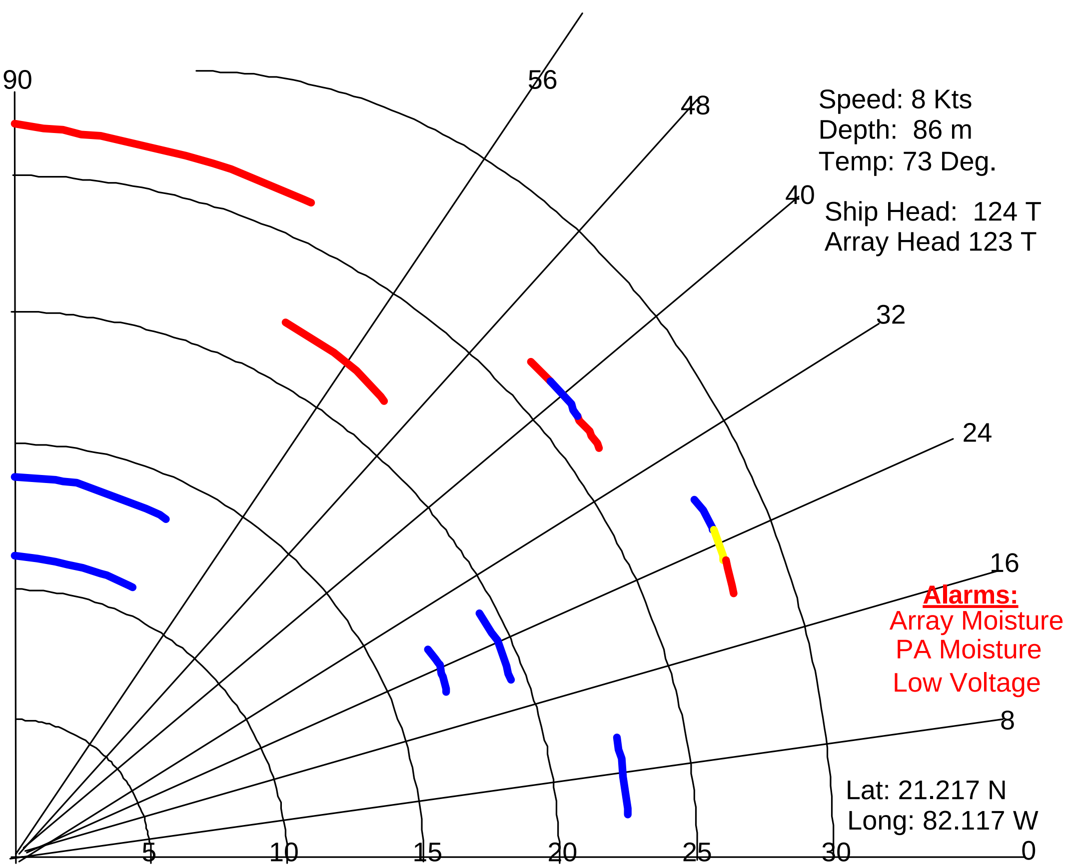

Figure 16 Local Display Configuration

Remote Display

An optional display potential is to ship contact-only symbols from the sonar to display onto the ship's radar display via the standard NMEA data interface. This concept has the ability to combine information in the "data fusion" fashion of a common display that the operator is already conditioned to observe. The difficulties with the concept are the possibility that the enactment of the standard may have several manufacturer dependent implementations, requiring new software for each radar system. It is presented here as a future upgrade that would reduce unique displays and enhance utilization of the system.

Deployment

The prototype system will be deployed off the starboard side of the seiner (either side of another research vessel) via the winch system. The array, after being coupled to the cable, is dropped tail first over the side. Cable is then paid out to a predetermined depth where the projector will be attached. The transmitter assembly, already connected to it's separate cable, is coupled to the receive cable with a Chinese Finger. As the 2 cables are deployed, zippered fairing will be installed to tie the 2 cables together and prevent fouling.

In an optional scenario, the receive array will be deployed by itself. The transmitter will be on the end of a leeboard, with all cabling internal. The board is normally carried alongside the ship, attached at a pivot point and a winch wire. To deploy, the board is winched from the horizontal to vertical position.

Retrieval of each system is the reverse sequence.

Data Collection and Testing

Two levels of testing are required to assure proper functioning of the system: component and system. While MIL-SPEC requirements are excessively formal and not necessarily cost effective, the underlying philosophy of determining the functionality of components before assembly to the subsystem level, and again at the system level. However, innovative and cost-effective measures should always be considered.

Critical components that must function to particular levels (ie specifications) are:
- Ceramic element and electronics for noise.
- ADC rates and syncronization.
- Data throughput of computer and interface cards.
- Software for bugs before integration.

At the subsystem level, these components must play together in a similar fashion. The critical subsystem tests are:

- Array elements to determine extent of vertical discrimination.
- Array for beampattern.
- Elements and pre-amplifiers for electrical noise.
- Receive towed-array for flow noise.
- Transmit output levels over the bandwidth.
- Receive levels in beam over bandwidth.
- Control signals to remote display
- Winch operation, with appropriate shieve size.

At the completion of the subsystem tests, system level operability and calibration must be done. Target strength data must be taken off of calibrated targets at the frequencies 3 and 4 KHz, with special attention to the 4 KHz data. The CW frequency (4 KHz) will be a primary search frequency and the TS data will be an important queue in the classification process. Linearity can be assumed between the 2 frequencies. Targets will need to be in the range of -5 to +8 dB to bracket the range of expected TS values. Tests will be conducted in a known environment (temperature and salinity structure, and bathymetry), as the system is too large to move into a controlled environment (eg. test tank). Returns will be generated in all beams in order to verify proper generation of the beam. At the completion of these tests, the system is now ready for open ocean testing on *in vivo* targets.

The data collection plan calls for eningeering tests to occur in local waters at the end of the first year of the construction. In the 2nd year, primary testing aboard research vessels and small tuna boats is scheduled to assure correlation between detection and identification. Since the fishery can move significantly from year to year, boats of opportunity will be used. In the 3rd year, scheduling trips aboard the larger seiners should result in real tests of the abilities of the system. Again, the emphasis is on fishing on the detections to determine validity of the system performance. Phase II is expected to take 3 years, including construction of the system and testing. The testing schedule is as follows:

- Year 1: build the system and depending on parts supplies, begin engineering tests identified above.

- Year 2: Conduct in-water tests aboard research vessels and tuna seiners of opportunity. Refine the system displays and deployment procedures. Emphasis is on validating identifying targets to fully characterize the system.

- Year 3: Conduct deep-water testing aboard large tuna seiners. Schedule and pay ship time to assure validation of targets can be accomplished, as well as ships of opportunity.

Budget.

The following price quotes were obtained conditioned on timely orders, thus can only be considered as estimates. Items in parenthesis identify a source and model.

Item	Unit Cost	Quantity Necessary	Cost
2. Projector (ITC-2010)	$15,954	1	$15,954
3. Power Amp Assy (Instruments Inc.)	$11,100	1	$11,100
• PA (S26-4) ($3400*2)			
• Transformer (est $1000)			
• High Power Switching network ($1000)			
• P/S on deck (via Instruments Inc) (~$3000)			
4. Projector Winch (source?) - use on deck gypsy winch -	1000	0	$ 0
5. Projector Cable (50m, estimate) + connectors ($250 ea.)	$10	50	$1,000
6. Projector Tow Body/PA housing, mechanical connections (estimate)	$1000	1	$1,000
7. Receive Elements (ITC-1010A) NOTE: pricing for 2 receive arrays (1 spare)	$1400	20*2	$56,000
8. Tow cable (South Bay Cable), 6 TSP, 0.63” dia., cost/m	$12.45	500	$6,225
9. Connectors at cable ends (Impulse, Canon, ...) 2 cables	$500	4	$2,000
10. In-water instrumentation bottle, mechanical connections, heat sync mountings (estimate)	$1000	1*2	$2,000
11. Nose housing, urethane potting, tow cable mechanical connection, compliant half-plane (estimate)	$1000	1*2	$2,000
12. In-water signal conditioning	$3070	1*2	$6,140
• 19 BP filters (est $20 ea = $380)			
• 1 Mux w/ 19> inputs, (est. $50 ea. = $50)			
• 38 12-bit 64 KHz A/Ds (est. $50 ea. = $1900)			
• 38 low-noise pre-amps (est. $20 ea. = $760)			
13. Receive Winch (SOSI =$16,750)	$16,750	1	$16,750
14. “Wet” beamforming processor = P5-133 (or greater) PCIMCIA Plus Bus processor with I/O card to mux	$1500	1	$1,500
15. Topside Computer and Display (several vendors, approx. prices as of 6/97)	$3000	1	$3,000
• 200 MHz Pentium computer (~$2300)			
• 128 MB RAM			
• 4 GB HDD			
• SCSI bus (~$225)			
• writable CD (~$350)			
• 17” CRT			
16. Leeboard wing 45m x 1.2m x .3m to pivot above waterline and contain fairing for storage of receive array and deployment point. To be point of deployment of Projector contained in freeflooded lower end. Estimate.	$10,000	1	$10,000
17. System Total Hardware Cost			$134,669

Note: 1) 2nd array constitutes $33,070 of material cost.
2) Leeboard comprises an estimated $10,000 option.

Component Specifications Table

System, General Description:

This system is a bistatic sonar to operate in the Eastern Tropical Pacific (ETP) to detect and classify tuna (*Thunnus albacares, T.* species) with towed transmit and receive arrays to operate to a depth of 100m (400m max.). The projector is towed to more effectively utilize a surface duct (if one exists) and to provide portability. The receive array is towed to move it away from the ship's self noise field, and to position it below the characteristic thermal layer or effectively into the surface duct. The prototype system must be portable.

Individual system components are specified below:

Projection System:

Transducer:

Quantity	Specification
Bandwidth:	• 3-4 KHz required. • 1-4 KHz desired for future expansion.
SPL:	• >190 dB//µPa @ 1m over the bandwidth required with maximum 2 KVA drive • >195 dB//µPa @ 1m over the bandwidth desired with maximum 2 KVA drive
Impedance network:	• As necessary to achieve bandwidth and SPL.
Operating Range	• 0 to 50m free flooded • 35 to 90°F water cooled
Quantity:	• 1 required/system
Size/Weight:	• <20" for any dimension • <100 lbs. in air

Power Amplifier(s):

Quantity	Specification
Bandwidth:	• 1-5 KHz, nominal.
Output Impedance Load:	• Capable of driving load fully capacitive load to 0° phase and possibly slightly inductive • Z from 5000 to 5Ω
Output Power:	• ≥ 2 KVA over bandwidth and highly reactive load, required • ≥ 3 KVA over same conditions, for spare capacity

Power Supply:

Quantity	Specification
Output power:	• 4 KVA (250 VDC) required
DC to DC Converter	• 250 V to ±15 V, ± 12 V and ± 5 V, at least 1A, as required

Cable/Winch:

Quantity	Specification
Number/type of conductors	• minimum 2 Twisted-Shielded Pairs capable of 250V, 8A with <1% drop over length of cable, water-blocked, capable of 1000 lb. sustained load.
Length of cable	• 50m required
Mechanical Load	• 1000 lbs. including cable weight • Fair lower 25m • Strength member to be separated from electrical cable at tow body to remove mechanical load from electrical connector • Torque balanced strength member
Connectors:	• 4 pin water-proof to 100m at tow body • No mechanical load from cable • At winch end, as appropriate to selected winch
Winch size/strength	• To handle 50m of 2 TSP cable with torque counterbalanced strength member • Handle load of 500 lbs tow drag plus cable weight
Winch power	Hybrid 3 phase 440VAC electrical-hydraulic

Receiving System:

Hydrophones:

Quantity	Specification
Bandwidth	• 3-4 KHz required • 1-5 KHz for future expansion.
Sensitivity	• -186 dB//1V/μPa across required band without preamp • preamp noise <-155 dBV/√Hz
Operating range:	• 0 to 100m depth • 35 to 90°F
Quantity:	• 19 required per array • 40 desired for spare array
Size/weight	• <4” diameter • <12” long • <5 lbs each

Signal Conditioning:

<u>Quantity</u> | <u>Specification</u>

Bandpass Filter

- 3 - 4 KHz Butterworth 6-pole filter
- Potentially widen filter to 1-5 KHz
- 1 per hydrophone

Analog to Digital Converter (ADC or A/D)

- 12 bit resolution
- <1 bit electrical noise
- Sample rate 64KHz
- Small enough to fit inside towed array envelope
- Ability to synchronize all ADCs

DC to DC converter:

- ±15V to ±12V and ±5V as required
- Min. 1A at each voltage
- Quantity 1/array

Multiplexer - Demultiplexer:

- Simultaneous clamp and hold for minimum of 19 channels
- Speed: 64K Samples/sec
- quantity 1 "wet" end

Beamformer:

- General purpose Pentium-133 PCMCIA-Plus class or faster processor to generated 9 beams over required bandwidth with frequency dependent steering coefficients
- Develop broadband beams in realtime
- Ship beam data to topside computer via RS-232 link
- DMA I/O capacity
- at least 1 serial port

Processing/Display System:

<u>Quantity</u> | <u>Specification</u>

Computer:

- ≥133 MHz Pentium (class) CPU
- ≥32 MB RAM
- >3 GB HDD
- 17" monitor, ≤.28" dot resolution, non-interlaced SVGA
- 3.5" FDD
- serial/parallel ports

NMEA interface

- Hardware/software necessary to ship data to radar display.

Glossary

Jargon	**Definition**
A/D, ADC	Analog to Digital Converter, a DAC converts Digital to Analog.
dB//1 μPa	Pressure level expressed as a ratio referenced to a micro-Pascal converted to decibels by the operation 20*log10(P/ P_0), P_0 = 1μPa
dBV	Voltage ratio, expressed in dB as 20*$\log_{10}$(V/V_{REF}), V_{REF} = 1 V_{RMS}
MUX	Multiplexer, '-ing: collating data from N sources into a single stream N*length.
P_D, P_A	Probablilty of Detection, Probability of False Alarm
Q	Quality of a resonant system, measured as the frequency of resonance divided by the bandwidth at the ½ power points (Q = Fres/BW). A high Q system responds with great amplitude near resonance, and very little away from resonance.
SL	Source Level, a measure of output acoustic pressure, expressed in dB as a ratio of measured pressure to the reference of 1 μPa measured at 1m.
TL	Transmission Loss, expressed in dB as a ratio of loss in acoustic pressure or energy to some reference distance, often 1m.
TVR	Transmit Voltage Response, a measure of acoustic output from a projector expressed as a voltage ratio in dB, usually 1V_{RMS}. A TVA is the response to current.

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